Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

SUPERCONDUCTING DETECTOR MAGNET WORKSHOP

Sep 12 – 14, 2022
CERN
Europe/Zurich timezone

# Magnets for the Mu2e experiment

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For the Mu2e Experiment

September 12, 2022

**With contributions from the Fermilab Mu2e Solenoid Team:**

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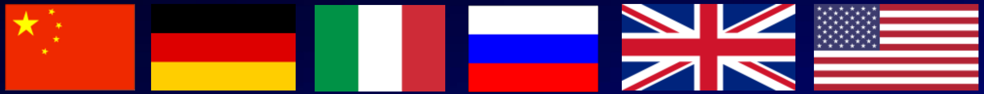
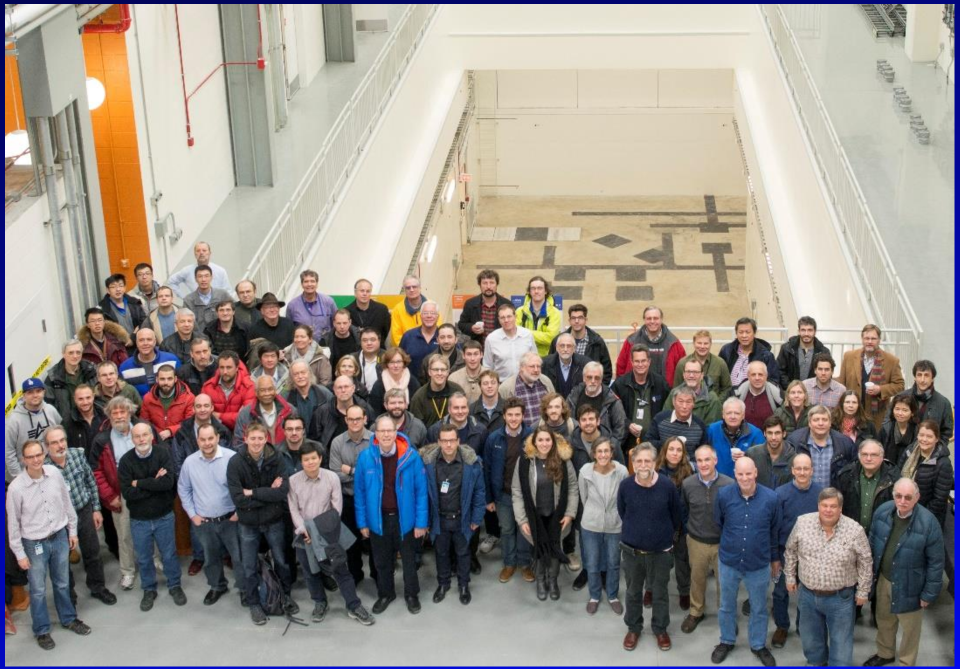
# THE MU2E COLLABORATION

Over 200 scientists from 38 institutions



The Mu2e Collaboration



Argonne National Laboratory ● Boston University
Brookhaven National Laboratory
University of California, Berkeley ● University of California, Davis ● University of California, Irvine
California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna
Duke University ● Fermi National Accelerator Laboratory
Laboratori Nazionali di Frascati ● INFN Genova
Helmholtz-Zentrum Dresden-Rossendorf ● University of Houston ● Kansas State University ● Lawrence Berkeley National Laboratory ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool
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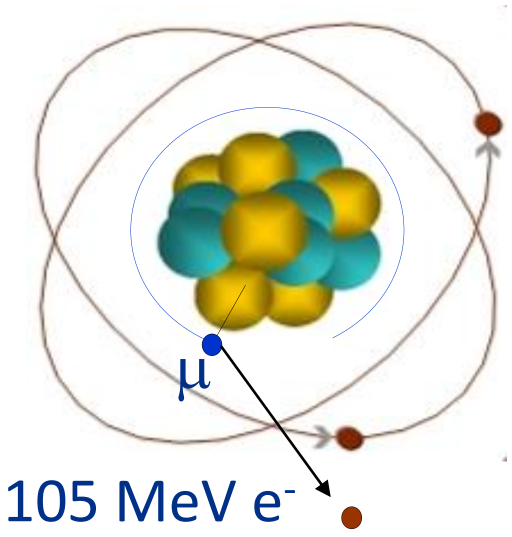
University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma ● University of Michigan ● University of Minnesota ● Institute for Nuclear Research, Moscow ● Muons Inc. ● Northern Illinois University ● Northwestern University
Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● University of South Alabama ● Sun Yat Sen University ● INFN Trieste
University of Virginia ● Yale University

# Mu2e Experiment Goal



- Search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of

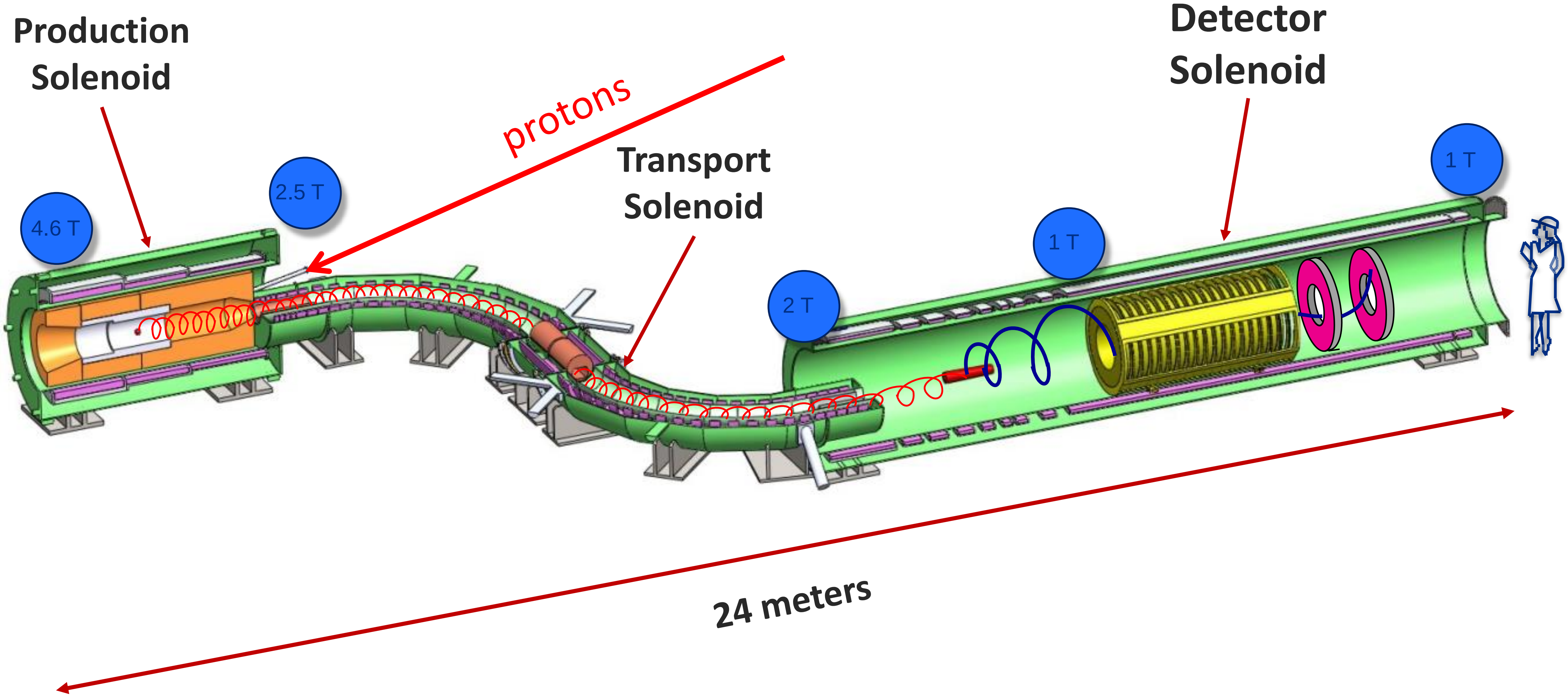
$$\mu^- N \rightarrow e^- N$$

- 4 orders of magnitude greater sensitivity than previous experiments
- If discovered, unambiguous evidence of physics beyond the Standard Model

# Mu2e Strategy

- Create muonic atoms: stop muons in orbit around an aluminum nucleus
- Look for events consistent with the signal
  - 105 MeV electron emanating from target
  - Clean experimental signature

# The Mu2e Experiment: 3 solenoids provide magnetic field



Production Solenoid

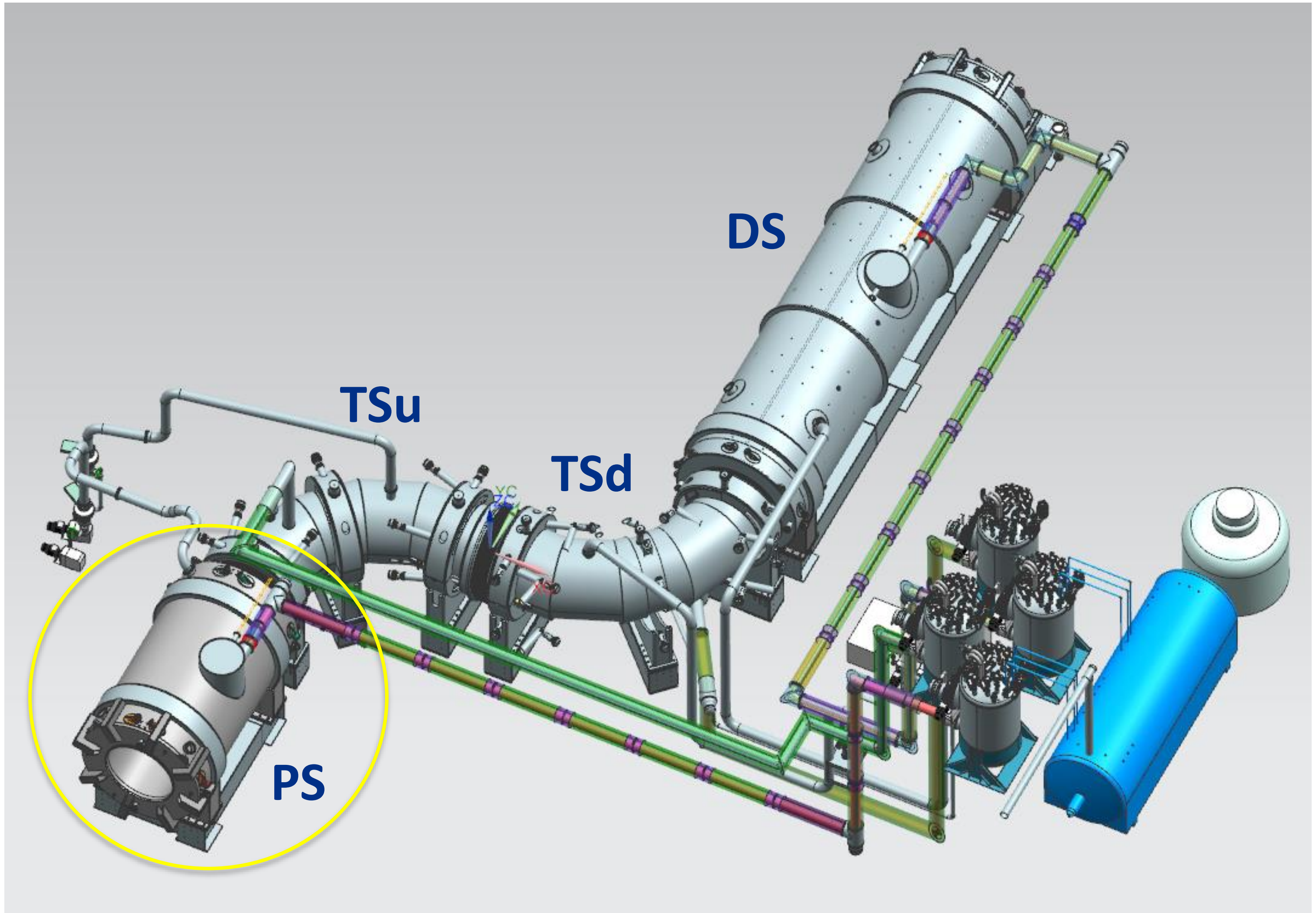
protons

Transport Solenoid

Detector Solenoid

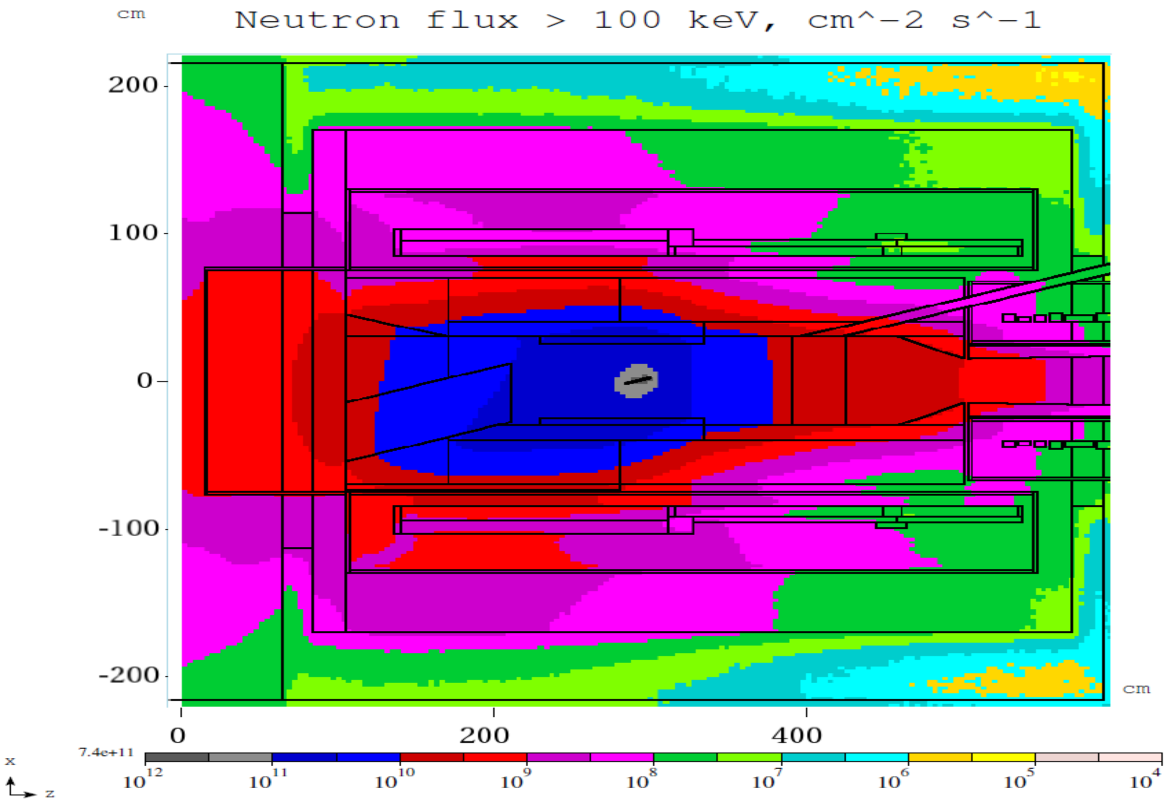
24 meters

# Production Solenoid (PS)

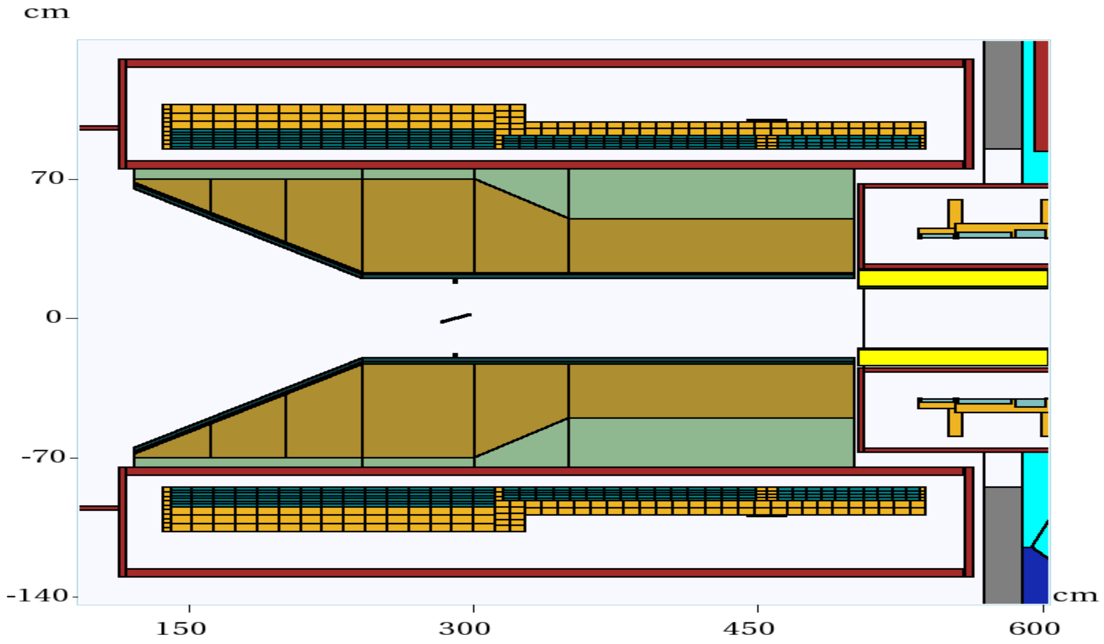


- 1.5 m warm bore, 4 m long
- 4.6 T to 2.5 T axial field
- Operating current ~9kA
- 3 coils  with 3-2-2 layers
- High-strength aluminum stabilized NbTi  superconductor (similar to ATLAS Central Solenoid)
- 5083-O aluminum outer support shells
- 5N aluminum thermal bridges to extract radiation heat
- Thermal Siphon Cooling
- Warm bore supports 55-ton Heat and Radiation Shield

# Unique PS feature: neutron radiation environment



| Parameter | Unit | Value |
|---|---|---|
| Peak absorbed dose | kGy/yr | 240 |
| Peak power density | μW/g | 13 |
| Total CM dynamic heat load | W | 28 |
| Peak DPA | 1/yr | $2.5\cdot10^{-5}$ |



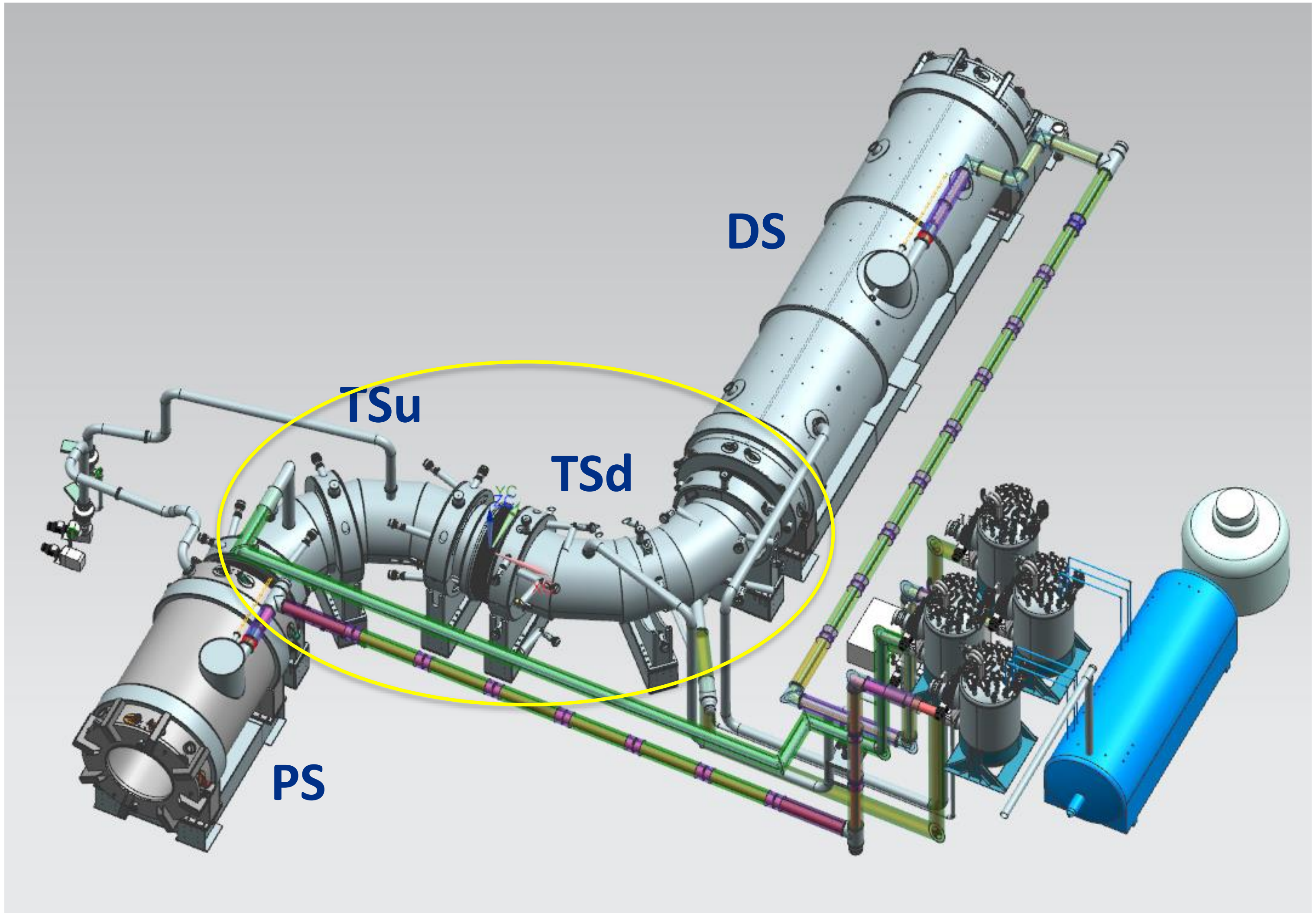
It is expected that RRR will degrade after one year of operation to the following critical values:

- Aluminum RRR 500 → 100;
- Copper RRR 100 → 50;

Once the critical degradation is detected (by RRR gauges on the coil), the magnet will be thermo-cycled to room temperature that recovers the RRR:

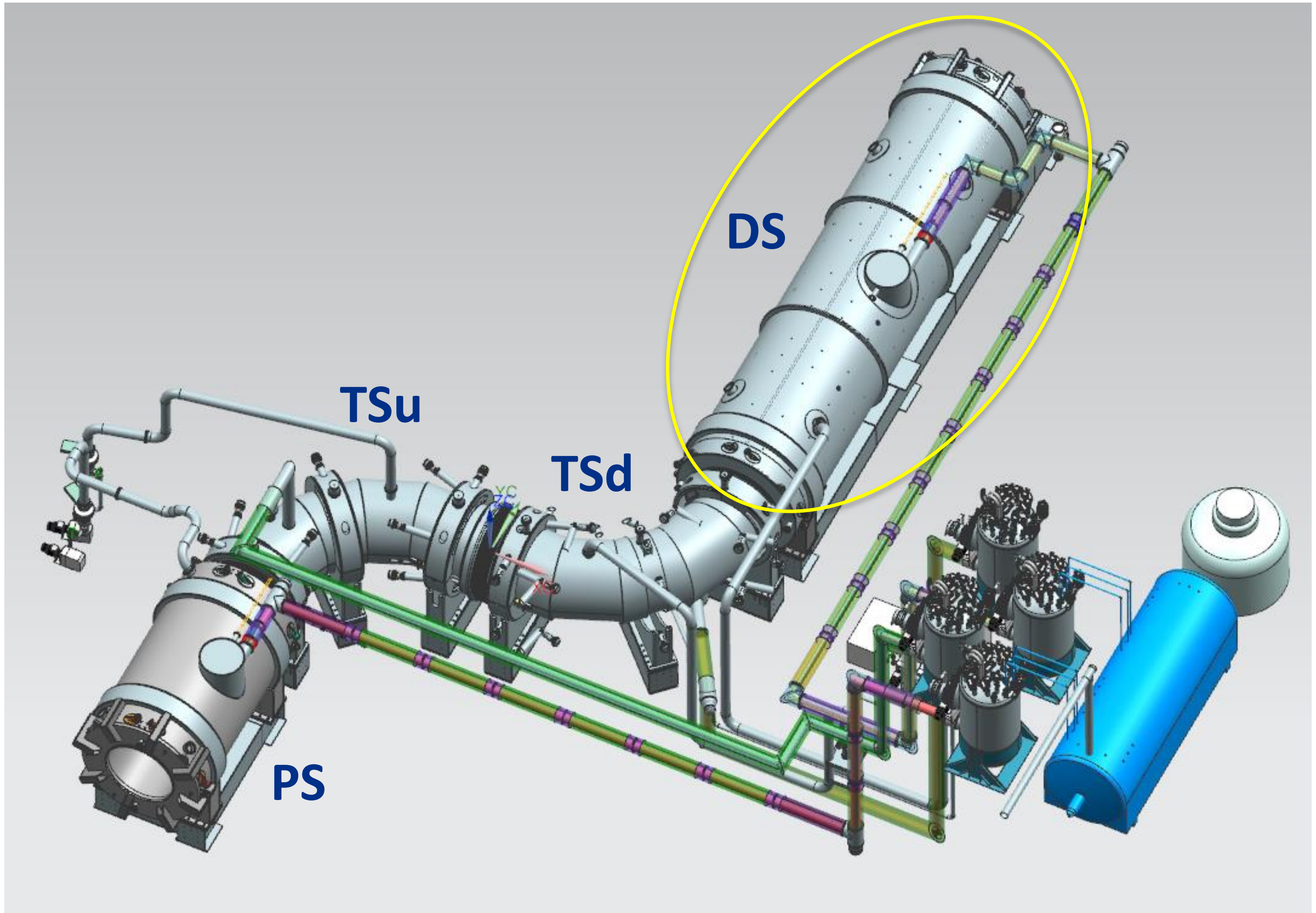
- 100% recovery for aluminum
- 85% recovery for copper

# Transport Solenoid (TS)



- 500 mm warm bore, 13 m long arch length
- 2.5 T at PS interface, 2.0 T at DS interface
- Monotonic negative gradient in straight sections
- Matching Toroidal fields for background suppression
- Unique magnetic field is formed by 52 SC solenoid coils organized into two cryostats: TSu and TSd.
- Each cryostat is powered by a separate 2kA power supply

# Detector Solenoid (DS)

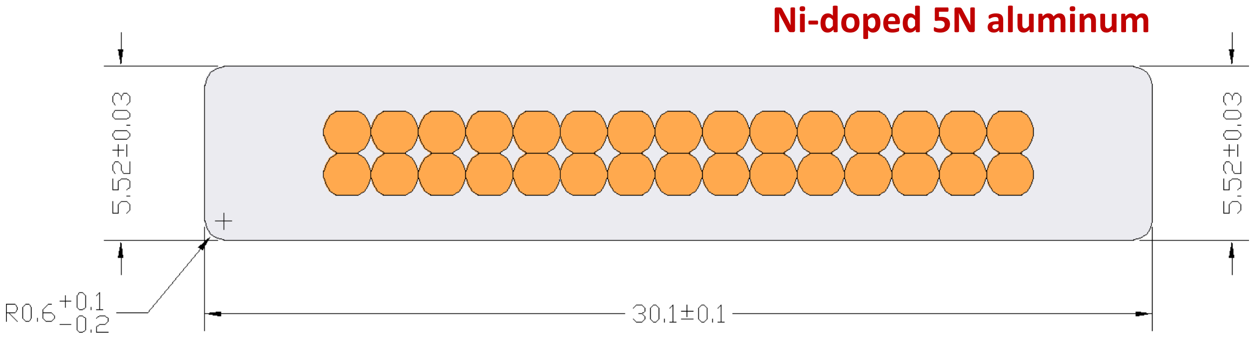


- 1.9 m warm bore, 10 m long
- Gradient Section 2T to 1 T field
- Spectrometer Section 1 T field with small axial gradient superimposed to reduce backgrounds
- Operating current ~6kA
- 11 coils in total
- Axial spacers in Gradient Section
- Spectrometer section made in 3 sections to simplify fabrication and reduce cost
- Magnet technology similar to PS

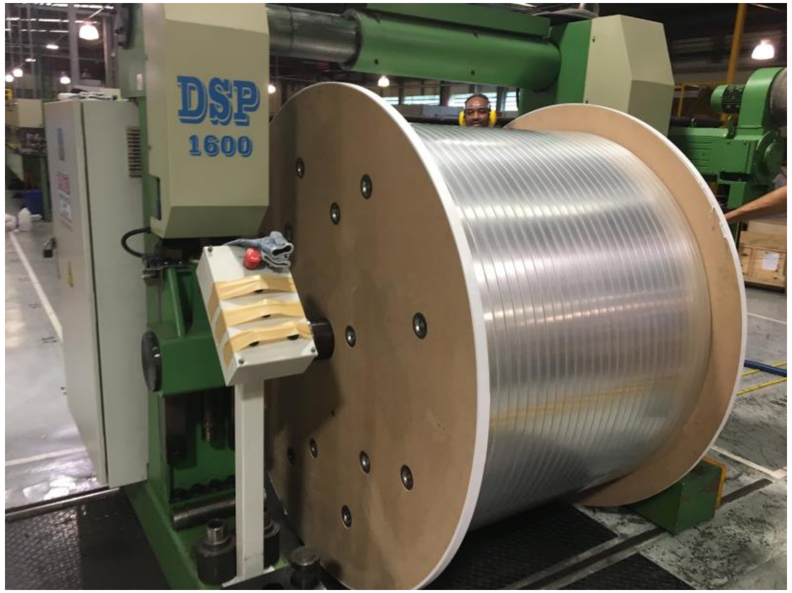
# Magnet status at a glance

- The magnet design work is complete
  - Reference and Technical Designs
- All aluminum-stabilized cables were fabricated by 2 vendors
  - QA and acceptance testing performed by vendors and Fermilab
- PS and DS magnets
  - are being built by a single vendor
  - Fermilab provides oversight and final acceptance testing
- TS magnet
  - all coil modules were fabricated by one vendor
  - coil acceptance testing performed by Fermilab
  - cold mass assembly completed at Fermilab
  - thermal shield and vacuum vessel assembly in progress at Fermilab

# PS cable

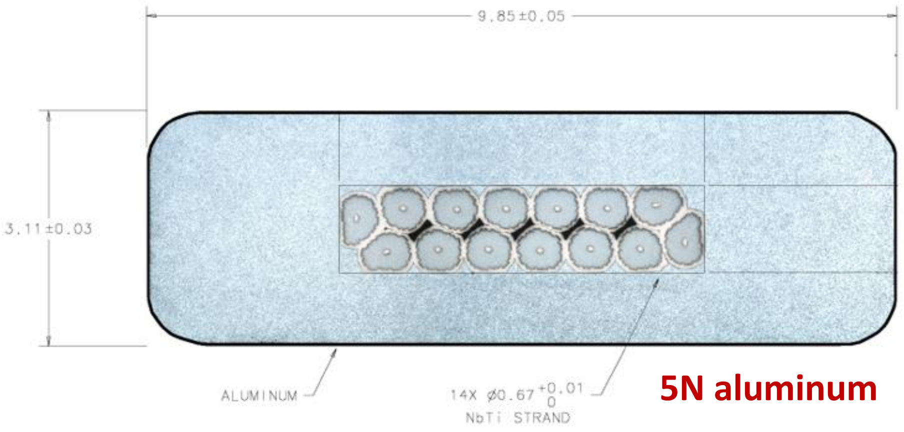


| Parameter | Unit | Value | Tolerance |
|---|---|---|---|
| Cable critical current at 5.0T, 4.22K | kA | ≥66.2 | |
| Cable critical current at 5.0T, 6.60K | kA | ≥9.2 | |
| NbTi filament diameter | μm | <40 | |
| Strand diameter at 293K | mm | 1.466 | ±0.005 |
| Number of strands | - | 30 | |
| Strand Cu/non-Cu ratio | - | 0.90 | ±0.05 |
| RRR of Cu matrix | - | ≥100 | |
| RRR of Al stabilizer | - | ≥500 | |
| 0.2% yield strength of Al stabilizer at 4.2K/293K | MPa | ≥80/60 | |
| Shear strength of Al-Cu bond at 293K | MPa | ≥40 | |
| Overall cable width at 293K | mm | 30.1 | ±0.1 |
| Overall cable minor edge thickness at 293K | mm | 5.52 | ±0.03 |
| Total delivered cable length | km | ≥14.4 | |



*Pictures courtesy of Furukawa Electric*

# TS cable



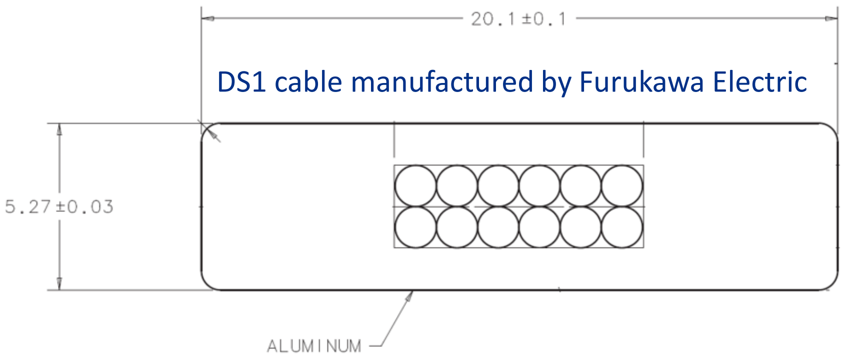
5N aluminum

| Conductor Parameter | Unit | Design Value |
|---|---|---|
| Cable critical current at 5T, 4.22K | A | 5900 |
| Number of strands | | 14 |
| Strand diameter | mm | 0.67 |
| Strand copper/SC ratio | | 1 ± 0.05 |
| RRR of Cu matrix | | > 90 |
| Filament size | µm | < 30 |
| Strand twist pitch | mm | 15 ± 2 |
| Rutherford cable width | mm | 4.79 ± 0.01 |
| Rutherford cable thickness | mm | 1.15 ± 0.006 |
| Al-stabilized cable width (bare) at room temperature | mm | 9.85 ± 0.05 |
| Al-stabilized cable thickness (bare) at room temperature | mm | 3.11 ± 0.03 |
| Initial RRR of Aluminum stabilizer | | > 800 |
| Aluminum 0.2% yield strength at 300 K | MPa | > 30 |
| Aluminum 0.2% yield strength at 4.2 K | MPa | > 40 |
| Shear strength between Aluminum and NbTi strands | MPa | > 20 |

See “Production of Aluminum Stabilized Superconducting Cable for the Mu2e Transport Solenoid” IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 28, NO. 3, APRIL 2018

*Pictures courtesy of Hitachi Cable*

# DS cable

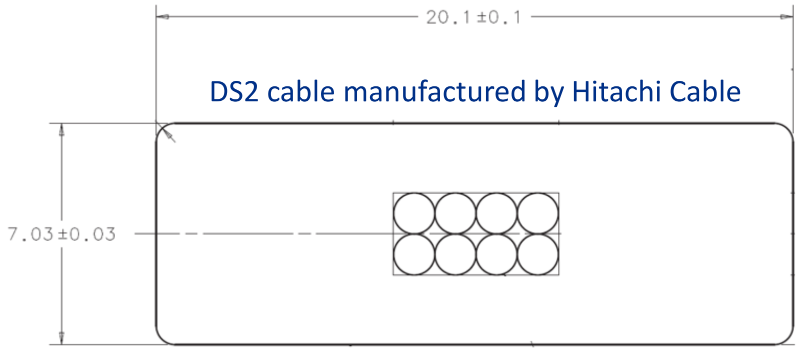


DS1 cable manufactured by Furukawa Electric

**5N aluminum**

DETECTOR SOLENOID 1 AL-STABILIZED CABLE MAIN PARAMETERS

| Quantity | As designed |
|---|---|
| Aluminum Stabilizer | 99.998% |
| Cable width at 293 K | 20.1 ± 0.1 mm |
| Cable thickness at 293 K | 5.27 ± 0.03 mm |
| Cable $I_c$ at 5 T, 4.22 K | ≥ 25000 A |
| Copper RRR | ≥ 80 |
| Aluminum RRR after cold-work | ≥ 800 |
| Al 0.2% yield strength at 293 K | ≥ 30 MPa |
| Al 0.2% yield strength at 4.2 K | ≥ 40 MPa |
| Al-Cu Shear Strength at 293 K | ≥ 20 MPa |



DS2 cable manufactured by Hitachi Cable

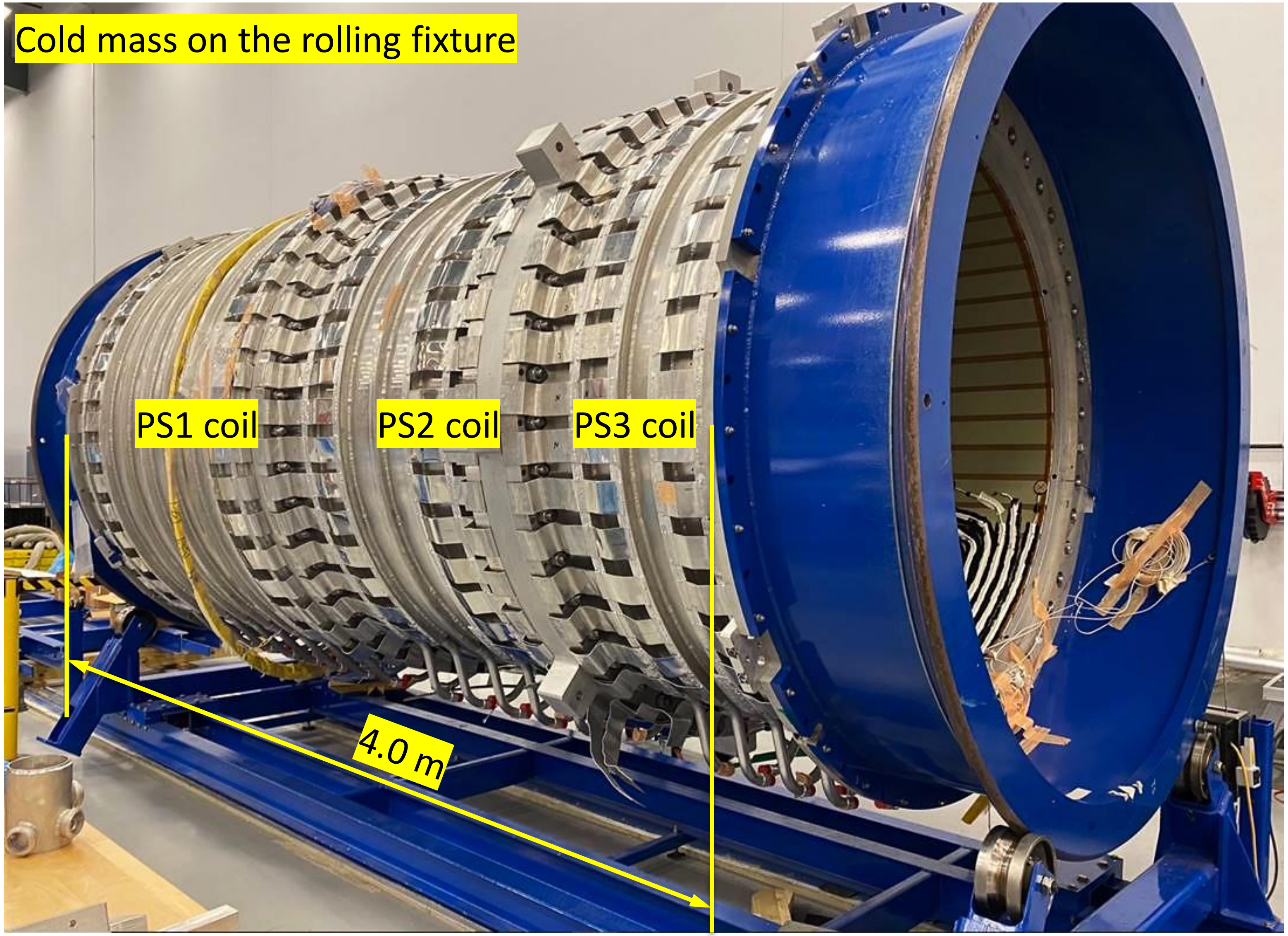
DETECTOR SOLENOID 2 AL-STABILIZED CABLE MAIN PARAMETERS

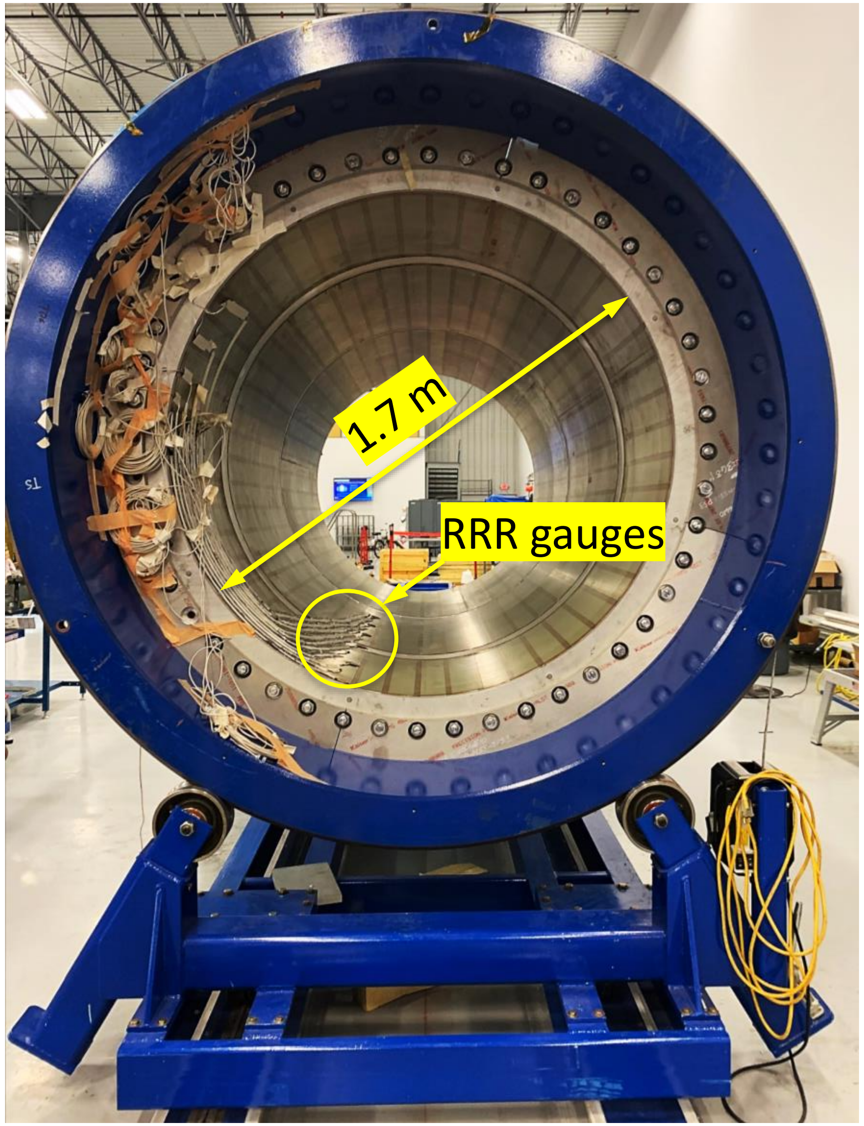
| Quantity | As designed |
|---|---|
| Aluminum Stabilizer | 99.998% |
| Cable width at 293 K | 20.1 ± 0.1mm |
| Cable thickness at 293 K | 7.03 ± 0.03 mm |
| Cable $I_c$ at 5 T, 4.22 K | ≥ 12500 A |
| Copper RRR | ≥ 100 |
| Aluminum RRR after cold-work | ≥ 800 |
| Al 0.2% yield strength at 293 K | ≥ 30 MPa |
| Al 0.2% yield strength at 4.2 K | ≥ 40 MPa |
| Al-Cu Shear Strength at 293 K | ≥ 20 MPa |

*See "Development of Aluminum-Stabilized Superconducting Cables for the Mu2e Detector Solenoid"* IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 4, JUNE 2016

*Pictures courtesy of Hitachi Cable*

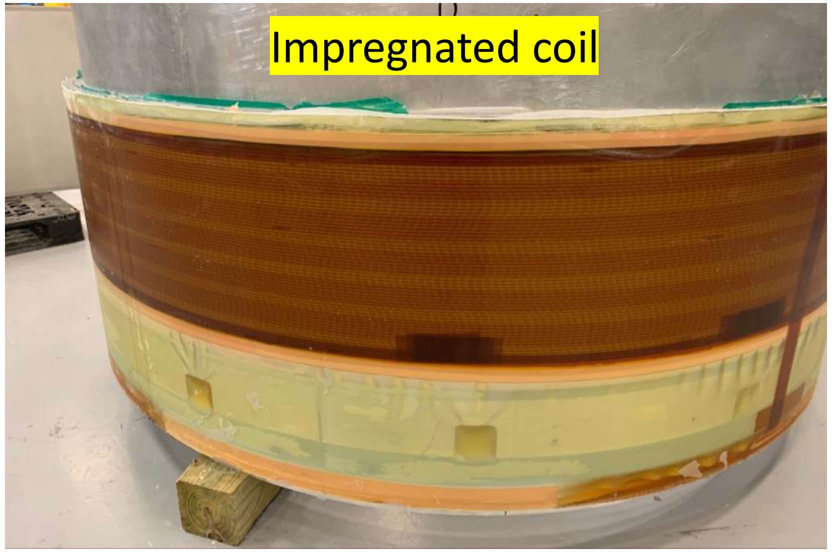
# PS fabrication: cold mass assembly





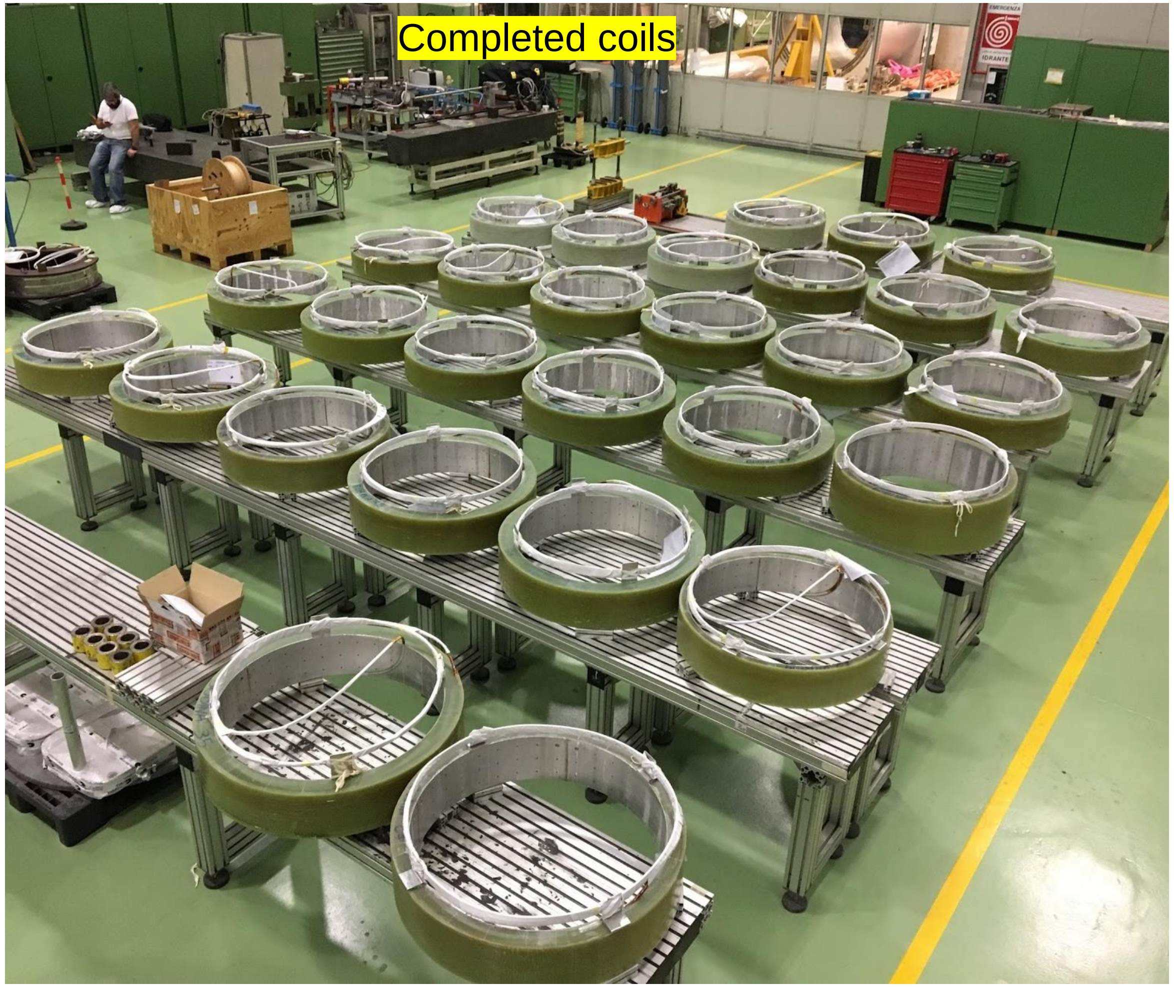
*Pictures courtesy of General Atomics*

# DS fabrication: coil production

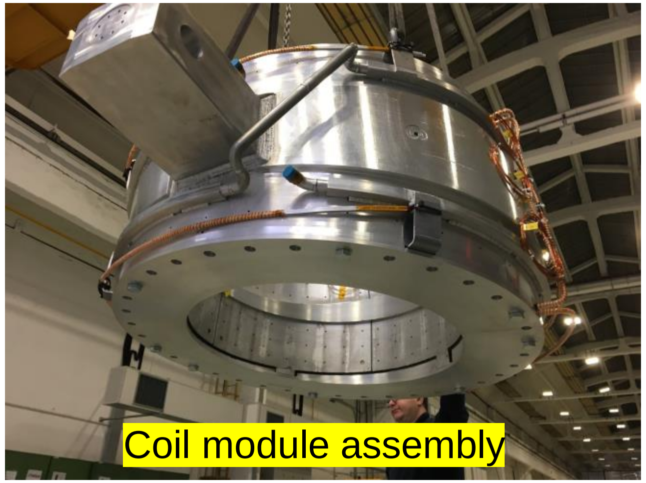


*Pictures courtesy of General Atomics*

# TS cold mass fabrication successfully completed


Completed coils

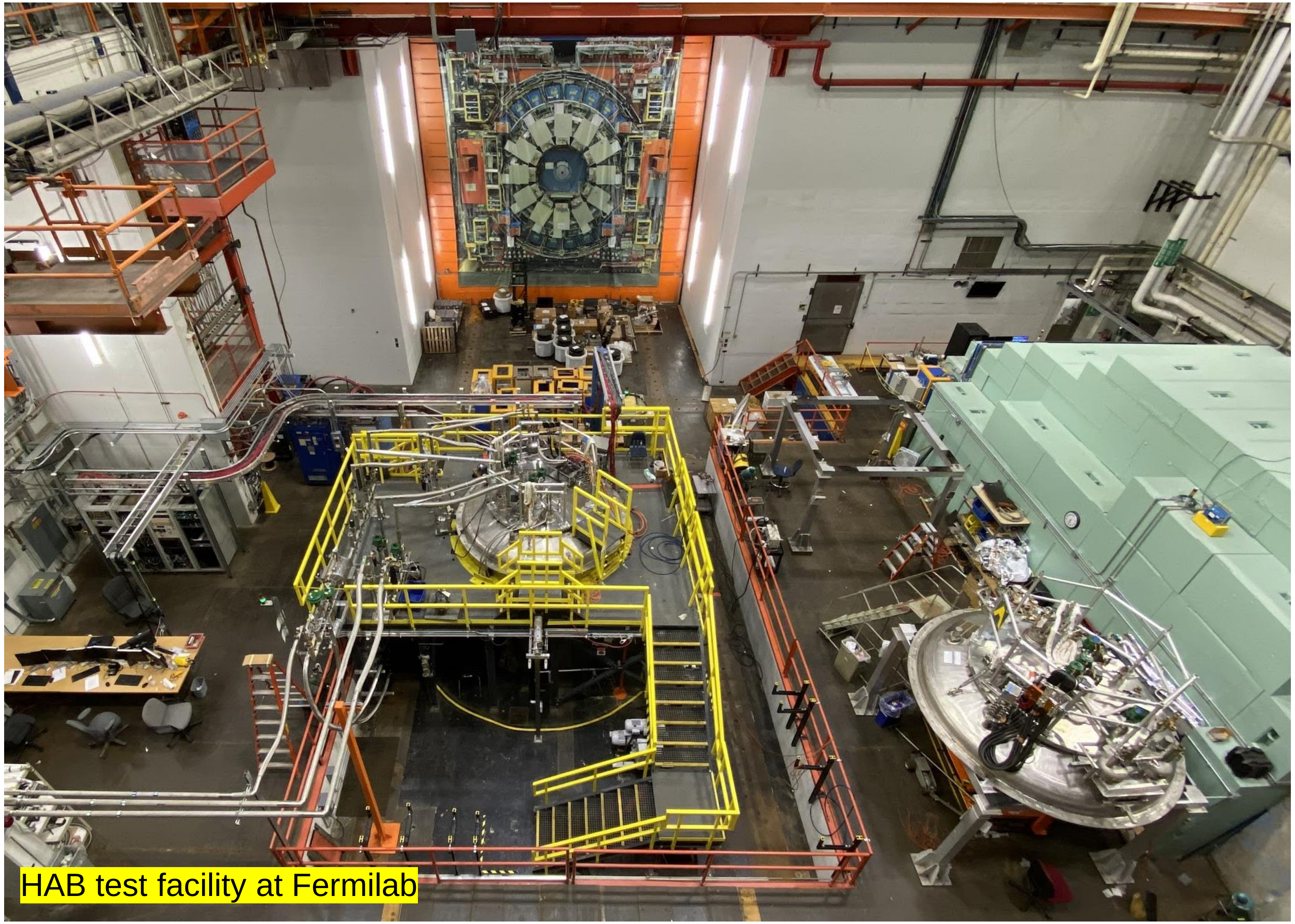

Shell insertion


Coil module assembly

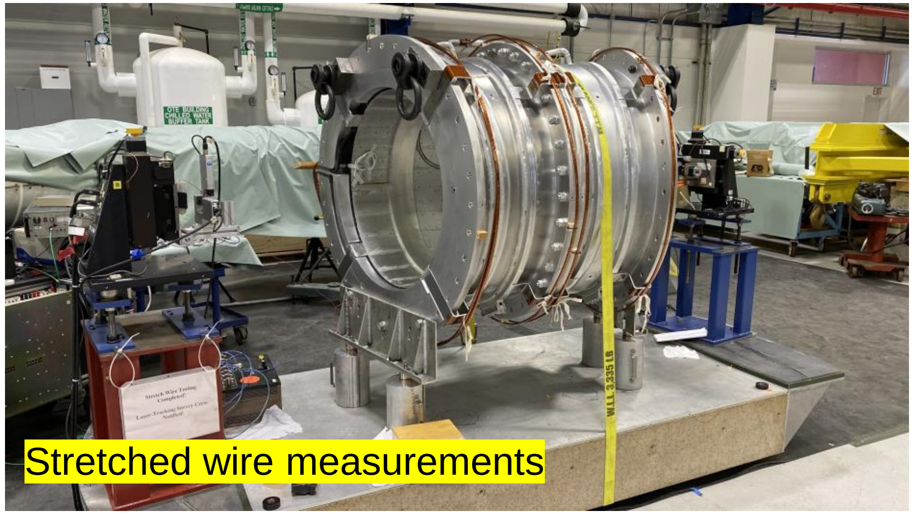

Packing for shipment

*Pictures courtesy of ASG Superconductors*

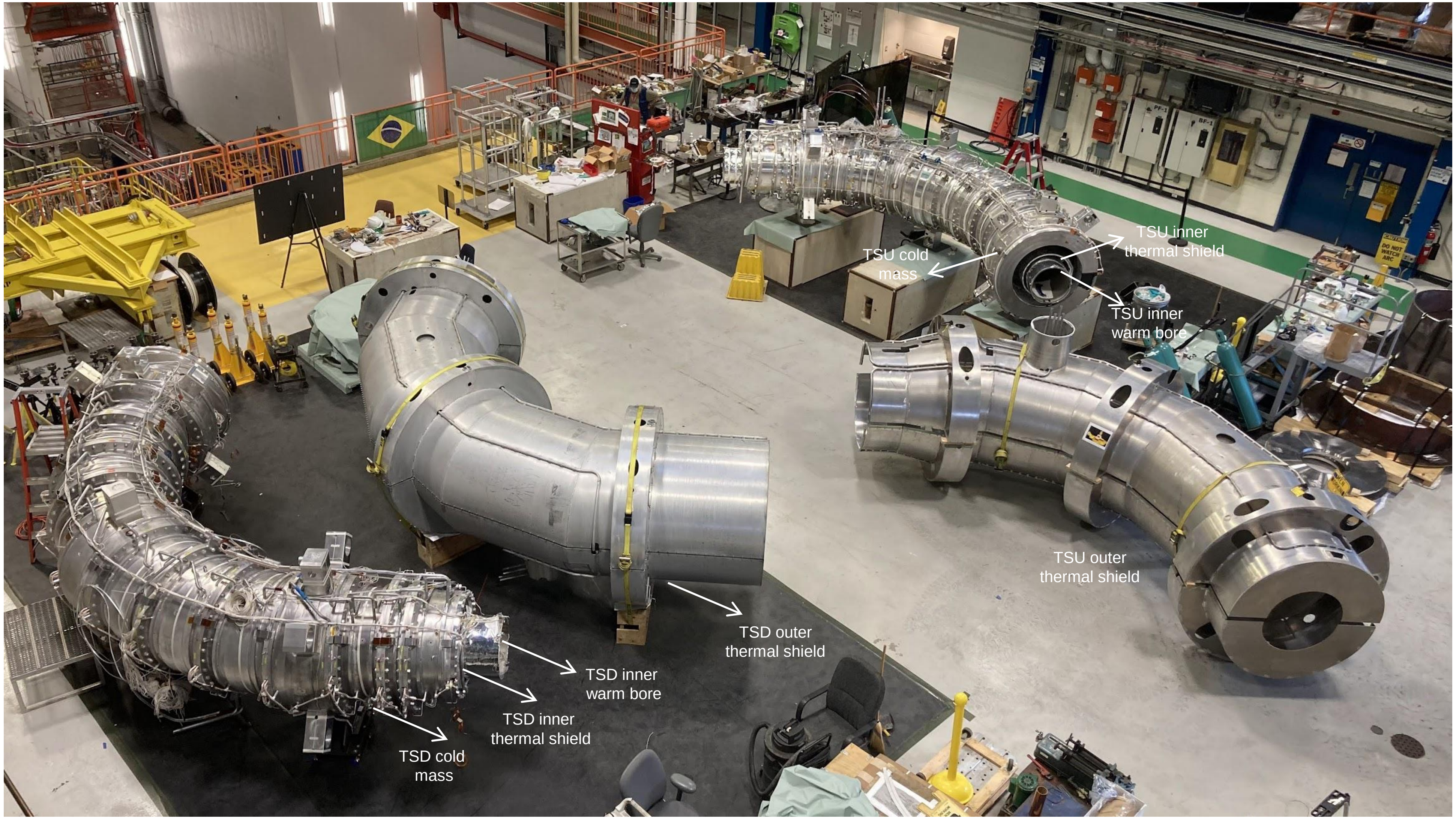
# TS coil acceptance testing successfully completed


HAB test facility at Fermilab

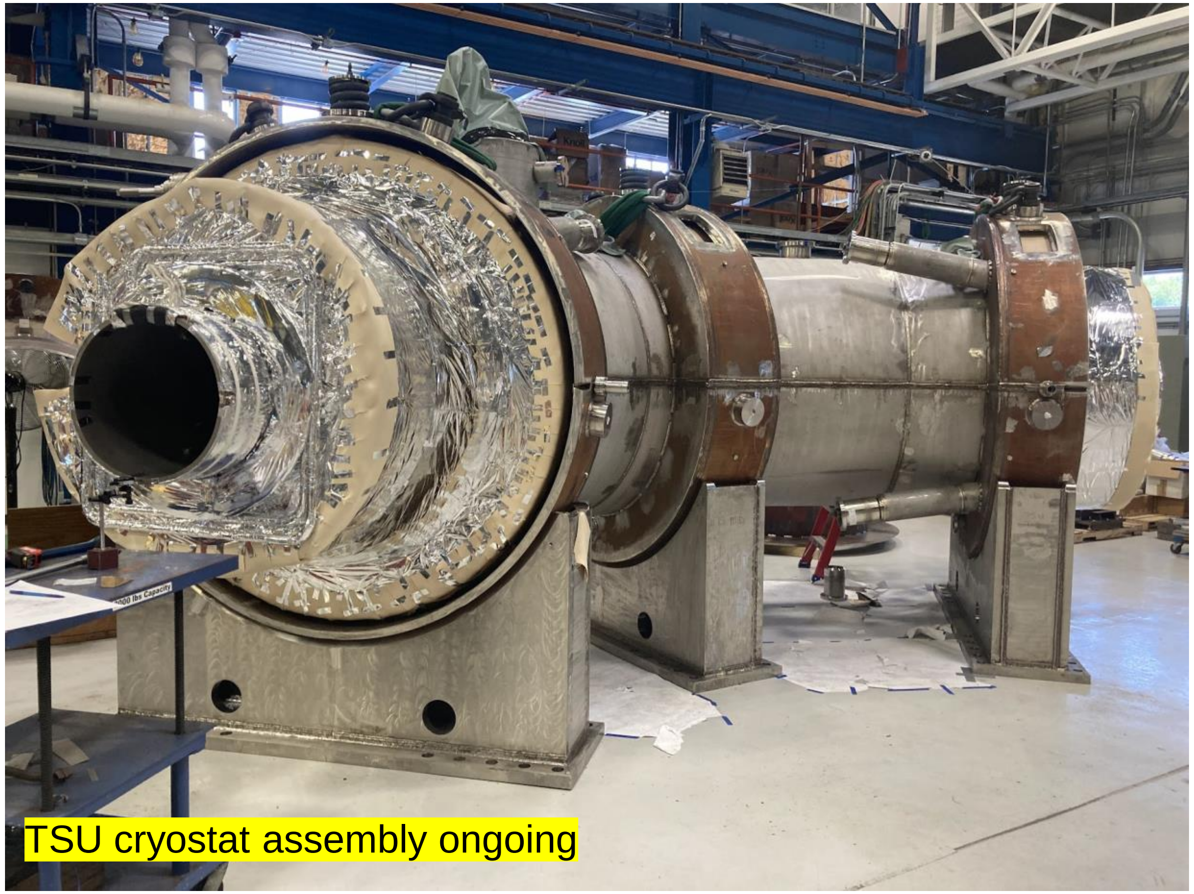

TS unit prepped for cold test


Stretched wire measurements

# TS cold mass and thermal shield assembly at Fermilab



# Current status of TS assembly at Fermilab


TSU cryostat assembly ongoing


TSD thermal shield assembly completed

# Planning for the future: Mu2e-II

Mu2e-II is a natural evolution of Mu2e that provides the nearest-term next step in a possible muon program at Fermilab. After the PIP-II linac construction, Mu2e-II will have access to 100 kW proton beam vs. 8 kW beam in Mu2e experiment. It allows an order of magnitude gain in sensitivity and discovery reach over Mu2e.

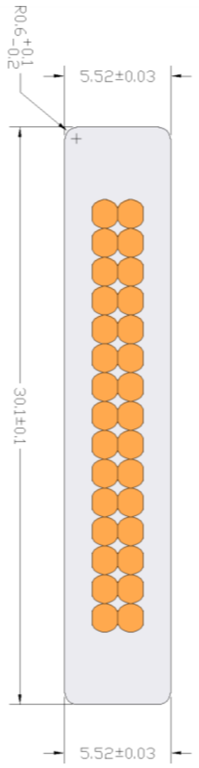
The main challenge for the magnetic system is that PS magnet will see a proportional increase of the neutron radiation load coming from the production target.

- The Mu2e PS magnet likely has to be replaced
- The magnet and the cooling system should be redesigned to cope with a factor of ten higher heat load
  - Conduction cooling no longer seems to be an option
  - Direct cooling by LHe may be the only feasible solution to extract the heat from the coils
- Cable-in-Conduit Conductor (CICC) could be a natural choice; however, it has several drawbacks:
  - High-density materials (Cu for the stabilizer and SS for the conduit). Would triple the heat dissipations and the load on the cryo-system comparing with the Al-stabilized conductors;
  - May have to use $Nb_3Sn$ (expensive and difficult to work with) instead of NbTi to cope with the higher thermal load;
  - RRR of Cu permanently degrades under neutron irradiation, while RRR of Al completely recovers during a thermo-cycle;

For these reasons, a different technical solution is being considered for Mu2e-II

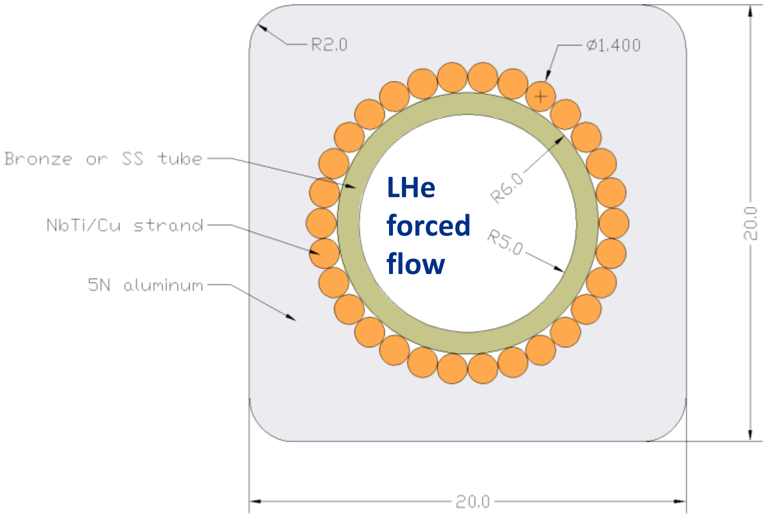
# Mu2e-II solution: internally-cooled aluminum stabilized cable

Regular Al-stabilized cable

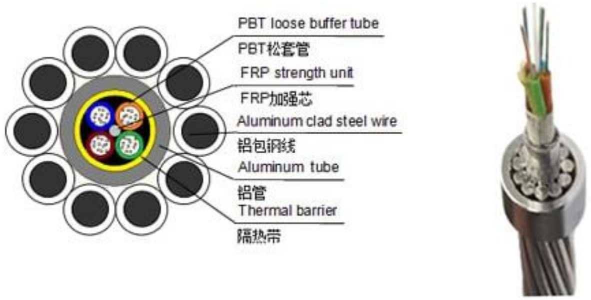


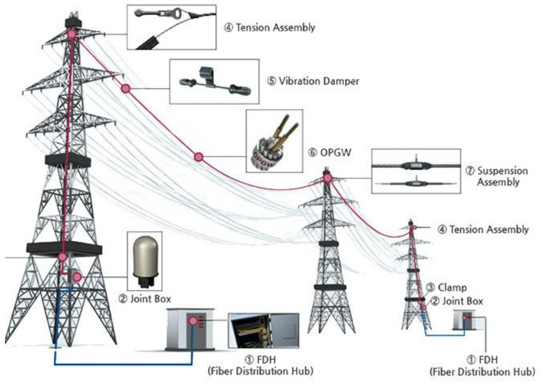
- Nearly direct cooling of superconductor by LHe
- Mostly low-density materials
- No permanent stabilizer degradation under irradiation

CICC



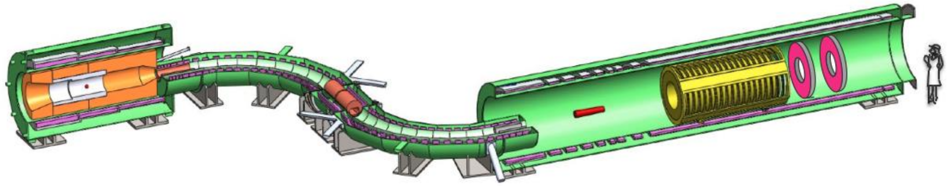
OPGW





- OPGW fabrication technology serves as an example that it can be done
- Still requires a dedicated R&D with cable vendor to develop a proof of principle cable
- A preferred solution for Mu2e-II

# Summary



- The Mu2e experiment is to search for Charged Lepton Flavor Violation to probe the physics beyond the Standard Model.
- The Mu2e magnet system consists of three solenoid magnets that use four types of aluminum-stabilized cables to meet the physics requirements.
- The magnet construction is well under way.
- Mu2e-II is being considered as a natural successor of Mu2e. It is a challenging upgrade that will require a dedicated cable and magnet R&D.